RevMexAA (Serie de Conferencias), **33**, 108–112 (2008)

THE EXTRAORDINARY LBV/WR SYSTEM HD 5980

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RESUMEN

Presentamos resultados de los cálculos para HD 5980 efectuados con nuestro modelo de interacción por fuerzas de marea. El modelo predice una mayor actividad atmosférica después del paso por el periastro, así como una mayor actividad ocasional en zonas intermedias entre el ecuador y el polo.

ABSTRACT

The LBV/WR system HD 5980 contains a short-period, eccentric binary system with interacting stellar winds. In this paper we summarize results from model calculations of the tidal flows on the LBV component showing that energy dissipation rates, $\dot{E}$, associated with turbulent viscosity are orbital-phase dependent as well as variable over the stellar surface. We speculate that if $\dot{E}$ contributes towards driving mass-loss, the strongest wind-wind interaction effects may occur *after* periastron passage. In addition, the model suggests the presence of stronger outflows localized at polar angles $\theta \sim$30–50° than over the rest of the stellar surface during part of the orbital cycle. Thus, the analysis of wind-wind interactions in this system requires a modified model in which non-stationary and asymmetric wind structures are incorporated.

Key Words: binaries: close — stars: individual (HD 5980) — stars: winds, Outflows

1. ERUPTIONS, WIND-WIND INTERACTIONS AND TIDES

HD 5980 is an amazing system. Niemela (1988) was the first to point out that it consists of two Wolf-Rayet-like components referred to as *star A* and *star B* in a relatively close, eclipsing and excentric orbit (P=19.3, e$\sim$0.3) and a third source, referred to as *star C*, that may simply lie along the line-of-sight to the close pair. The spectral characteristics and visual brightness of the system underwent significant changes between the late 1970's and 1993, when it entered an eruptive state that lasted $\sim$1 year (Bateson & Jones 1994; Barbá et al. 1995; Koenigsberger et al. 1995). The activity involved an increase in visual brightness and mass-loss rate, and a decrease in wind velocity and effective temperature, similar to the eruption phenomena observed in luminous blue variables (LBVs). The radial velocity variations observed in the very rich emission-line spectrum that appeared after the eruption led Barbá et al. (1996, 1997) to conclude that the instability producing the outbursts originated in star A. A detailed review of HD 5980's properties is provided by Koenigsberger (2004).

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The ZAMS masses of star A and star B are inferred to be $\geq$100 $M_\odot$ (Koenigsberger 2004). The substantial mass loss required for them to have reached their current masses ($M_A \sim$50 $M_\odot$, $M_B \sim$30 $M_\odot$, Niemela et al. 1997) may have been achieved through multiple events as those of 1993/1994. LBV's are associated with the evolutionary state during which large quantities of mass are ejected allowing the star to reach the W-R phases with highly depleted hydrogen envelopes. With the possible exception of η Carinae, there is no known LBV with such a developed W-R spectrum as that displayed by HD 5980.

1.1. *A changing wind-momentum ratio*

The spectrum of HD 5980 in the late 1970's, with its broad He II and N V lines, was typical of the "early" W-R stars of the nitrogen sequence (WNE; van der Hucht 2001). This spectrum is believed to originate in the wind of star B. Over the next decade, however, numerous lines from lower-ionization atomic species appeared, implying a growing presence of a cooler stellar wind, which we now attribute to star A. Clearly, the emerging dominance of star A's wind implies changes in the wind-wind interaction (WWI) region characteristics.

Emission-line profile variations observed in optical and UV wavebands are phase-locked and should, in principle, provide information on the geometry of the changing WWI region (Moffat et al. 1998). Surprisingly, however, the nature of the variability has remained the same ever since it was first reported by Breysacher & Westerlund (1978) and quantified by Breysacher, Moffat, & Niemela (1982). The variations consist of periodic changes in width and degree of asymmetry as a function of orbital phase. Figure 1 illustrates the NIV] 1486 Å emission line variability: it is always narrower and sharply peaked near the eclipse when star B is "in front" (ϕ ∼0.40), while becoming broader and weaker when both stars are unocculted at ϕ =0.83. The three epochs that are displayed correspond to pre-eruption (1991), post-eruption (1999) and ∼ 1 year after maximum (1995). This persistent trend is unexpected since the geometry of the WWI regions depends on the momentum ratio of the stellar winds, a ratio that changed over time as star A's wind became more dominant. Thus, HD 5980 appears to provide another example of the discrepancies that arise when confronting the current WWI models with observations (see presentations in this Volume by Rauw, Williams, among others). But at the same time, because of the large observational database available for HD 5980, its behavior may provide a clue to identifying the source of the discrepancies.

1.2. *Tides and non-stationary, asymmetric winds*

Like many of the intriguingly active binaries, HD 5980 has an excentric orbit. In such systems, the tidal forces are time-variable. The preliminary exploration of tidal effects in HD 5980 led to the conclusion that they are non-negligible (Koenigsberger et al. 2002), and thus raised the question of whether they may be responsible for some of the system's peculiarities. Recent results of our calculations (Moreno & Koenigsberger 2007) indicate that the tidal flows near the stellar surface can liberate considerable amounts of energy through dissipative processes. The magnitude of the energy dissipation rate, $\dot{E}$, depends on the stellar and orbital parameters. In the following sections, we'll describe the two basic conclusions of the calculations: (1) maximum $\dot{E}$ occurs *after* periastron passage, not at periastron; and (2) at certain orbital phases, larger values of $\dot{E}$ are generated at intermediate polar angles than in the equatorial belt. These results are relevant for WWI theory if we assume that $\dot{E}$ contributes towards enhancing the stellar mass-loss rate. The winds in excentric binaries such as HD 5980 would then be *intrinsically* non-spherically symmetric and time-dependent, thus leading to discrepancies when comparing the observational diagnostics of WWI with the predictions of stationary models.

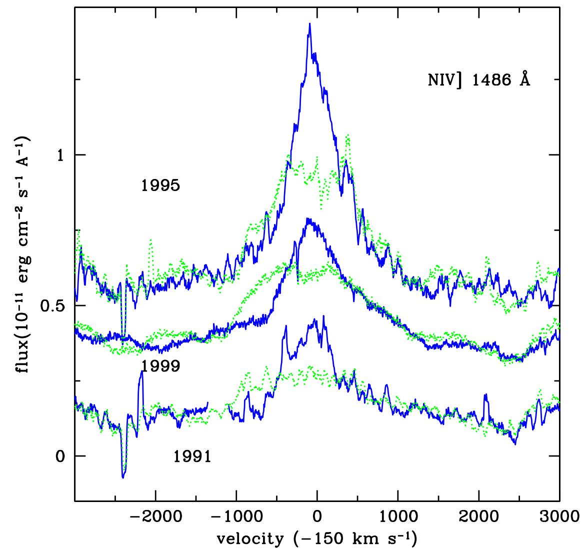

Fig. 1. Line profiles of the semi-forbidden N IV emission line at λ 1486 Å observed at two different orbital phases (ϕ ∼0.40 and 0.83 – dots) for each of three different epochs (1991, 1995 and 1999). The qualitative nature of the line-profile variations remains constant. Sets of profiles for different epochs are vertically displaced for clarity in the figure.

2. ENERGY DISSIPATION FROM TIDAL FLOWS IN HD 5980

Tidal effects are important when a star's rotation, ω, is not synchronized with the orbital motion, Ω. In excentric binaries, this is generally the case since the orbital motion varies with phase while the stellar rotation rate remains constant. There is no direct observation of $vsini$ for star A or star B. But the low-amplitude variations of star C's narrow absorption lines over the 19.3-day orbit has been interpreted in terms of contamination by very broad absorptions arising in star A but not visible due to their superposition on the emission lines (Georgiev & Koenigsberger 2004). Under this assumption, $vsini \geq 200$ km/s, thus providing an estimate for the ratio ω/Ω_{per} ∼2.33, where Ω_{per} is the orbital angular velocity at periastron. This means that star A rotates super-synchronously throughout the orbital cycle.

The basic method is described in Moreno & Koenigsberger (1999) and Moreno et al. (2005). With the recent extensions (Moreno & Koenigsberger, in prep.), the code now computes the amplitudes of the tidal flow in a thin surface layer over the entire stellar surface. These amplitudes are used to estimate the shear energy dissipation rates, $\dot{E}$ that arise from the relative motions of different surface

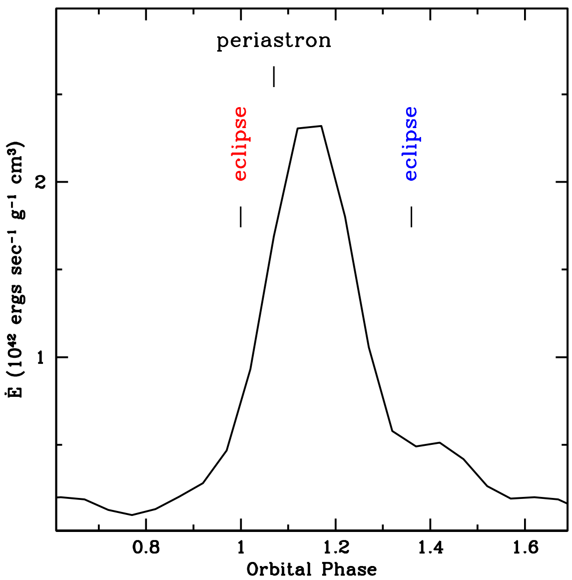

Fig. 2. Predicted energy dissipation rate per unit density due to the tidal flows on the stellar surface of star A as a function of orbital phase. Maximum rates occur *after* periastron passage. Star A is "in front" at ϕ=0, and periastron passage occurs at $\phi\sim$0.07.

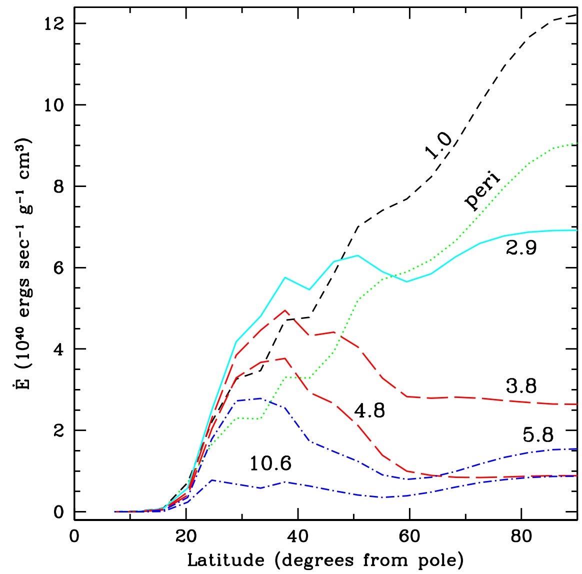

Fig. 3. Predicted energy dissipation rate per unit density due to the tidal flows on the stellar surface of star A as a function of latitude at periastron and several times (in days) after periastron passage. Note that $\dot{E}$ is greater at intermetidate polar angles ($\theta\sim$20–50°) than at the equator around $\sim$days 3–6 after periastron.

layers using an extension of the approach described in Toledano et al. (2006).

Figure 2 illustrates the time-dependence of $\dot{E}$ as a function of orbital phase from our HD 5980 model calculation. The first thing to note is that the maximum rates are generated after periastron passage, $\phi\sim$0.1–0.25, with minimum values around ϕ=0.8. Thus, it is tempting to suggest that the persistent line-profile variability shown in Figure 1 may be associated with the orbital-phase dependent changes in $\dot{E}$. But in what way do the tidal effects produce these variations?

The answer may lie in the distribution in latitude of $\dot{E}$. Figure 3 illustrates $\dot{E} = \dot{E}(\theta)$ for several different times within the orbital cycle. At periastron (dotted curve) and until $\sim$2 days thereafter, maximum $\dot{E}(\theta)$ occurs at the equator and systematically decreases towards the pole (θ=0 at the pole). By day $\sim$3 and until apastron, however, there is a distinct change in this trend whereby maximum $\dot{E}(\theta)$ now occurs at $\theta\sim$30–50°. If we assume that $\dot{E} \rightarrow \dot{M}$, the results shown in Figure 3 imply that between days $\sim$3 and $\sim$6 after periastron passage ($\phi\sim$0.2–0.4) mass outflow from regions at intermediate polar angles is more intense than from the equator. A denser "polar" wind would produce a narrower and sharply peaked emission-line profile, as seen in Figure 1 for $\phi\sim$0.40. Additional observational evidence for polar outflows within this orbital phase interval is provided by Villar-Sbaffi et al. (2003) who state that "the mass-loss of HD 5980 around ϕ=0.36 presented fluctuations in axial symmetry ranging from very rapid density enhancements along the orbital plane to polar ejections". At orbital phase $\phi\sim$0.8, $\dot{E}(\theta)$ has a relatively small gradient between the pole and the equator and is significantly weaker than near periastron. Thus, the stellar wind structure of star A should be more spherically symmetric at this phase.

Clearly, there are additional contributions to producing the line-profile variations, such as the physical and wind eclipses, as well as contributions from the WWI zone and all of these need to be considered. However, it is encouraging that the asymmetries in wind structure predicted by the tidal interaction model are consistent with the emission-line profile variability.

3. FINAL REFLECTIONS

A one-layer tidal interaction model for HD 5980 predicts that the energy dissipation rate due to the tidal shearing flows are time-dependent and non-spherically symmetric. Speculating that $\dot{E}$ contributes towards the stellar wind mass-loss, leads to the conclusion that $\dot{M}$ may also be locally enhanced near specific surface locations. In particular, outflows at intermediate polar angles may be stronger than at the equator at particular orbital phases. Furthermore, the model predicts that maximum $\dot{E}$ should occur after periastron passage, thus implying an overall enhanced $\dot{M}$ compared to other orbital phases.

Post-periastron events seem to occur in a wide variety of binary systems, such as WR 140, η Carinae and others, raising the question of whether the tidal effects described above are more prevalent than one may have anticipated. Is it possible that the stronger WWI effects ("outbursts") that occur after periastron passage are associated with stronger mass-loss rates at these phases induced by tidal instabilities? If this were the case, the source of the discrepancies between wind-wind interaction model predictions and the observations may simply reside in the assumption of stationary and spherically symmetric winds.

It is interesting to note that the hypothesis of enhanced $\dot{M}$ arising from $\dot{E}$ may not be entirely unreasonable. Given HD 5980's huge UV luminosity (see, for example, Koenigsberger 2004), it is likely to be on the verge of the Eddington Limit, as other W-R stars appear to be (Gräfener & Hamann 2008). Thus, small additions of energy in sub-photospheric layers could drive it to a super-Eddington state. We speculate that viscous shear energy dissipation resulting from the tidal forces may be a non-negligible contributor to this small needed additional energy.

Within this context, a final consideration concerns the sudden eruptive events in HD 5980. Monitoring of HD 5980 at visual and UV wavebands prior to, during and after its eruptions has yielded a unique data set that provide clues for constraining the eruption mechanism. For example, ultraviolet observations suggest that the onset of the eruptive state involved rapid transitions between a fast and a slow stellar wind (Koenigsberger 2004). Hence, it is likely that the eruption occurred when the wind became so dense that the bistability limit was crossed (Lamers, Snow, & Lindholm 1995). But this is only the symptom of a more deep-seated phenomenon that causes the instability leading to the enhanced density wind in the first place. Tidal effects are very sensitive to the star's radius. If HD 5980 (and other similar stars) are undergoing an evolutionary transition by which outer layers are expanding, the amplitudes of the tidal flows are expected to grow significantly. If the hypothesis that $\dot{E} \rightarrow \dot{M}$ can be shown to stand on firm ground, this would provide a mechanism to remove significant amounts of mass as the star tries to evolve towards the red end of the H-R Diagram. Whether the mass-shedding occurs as episodic eruptions, such as we've observed in HD 5980, or whether it is through a sustained high-density wind, requires an understanding of the $\dot{E} \rightarrow \dot{M}$ process. Since our model neglects the effects of intrinsic stellar oscillation modes, effective temperature variations and radiation pressure, we are unable to go beyond the speculative realm at this time.

GK thanks Jeff Kuhn and Stan Owocki for very helpful discussions. Support from PAPIIT/DGAPA grant IN119205 is gratefully acknowledged.

REFERENCES

Barbá, R. H., Niemela, V. S., Baume, G., & Vázquez, R. A. 1995, ApJ, 446, L23
Barbá, R. H., Niemela, V. S., & Morrell, N. I. 1997, ASP Conf. Ser. 120, Luminous Blue Variables: Massive Stars in Transition, ed. A. Nota & H. Lamers (San Francisco: ASP), 238
Barbá, R. H., et al. 1996, RexMexAA (SC), 5, 85
Bateson, F. M., & Jones, A. 1993, R. Astron. Soc. New Zealand Publ. Variable Stars, 19, 50
Breysacher, J., & Westerlund, B. E. 1978, A&A 67, 261
Breysacher, J., Moffat, A. F. J., & Niemela, V. S. 1982, ApJ, 257, 116
Georgiev, L., & Koenigsberger, G., 2004 in IAU Symp. 215, Stellar Rotation, ed. A. Maeder & P. Eenens (San Francisco: ASP), 111
Gräfener, G., & Hamann, W.-R. 2008, RevMexAA (SC), 33, 94
Koenigsberger, G. 2004, RexMexAA, 40, 107
Koenigsberger, G., Guinan, E., Auer, L. H., & Georgiev, L. 1995, ApJ, 452, L107
Koenigsberger, G., Moreno, E., & Cervantes, F. 2002, ASP Conf. Ser. 260, Interacting Winds from Massive Stars, ed. A. F. J. Moffat & N. St.-Louis (San Fracisco: ASP), 507
Lamers, H. J. G. L. M, Snow, T. P., & Lindholm, D. M. 1995, ApJ, 455, 269
Moffat, A. F. J., et al. 1998, ApJ, 497, 896
Moreno, E., & Koenigsberger, G. 1999, RevMexAA, 35, 157
Moreno, E., Koenigsberger, G., & Toledano, O. 2005, A&A, 437, 641
Niemela, V. S., 1988, ASP Conf. Ser. 1, Progress and Opportunities in Southern Hemisphere Optical Astronomy, ed. by V.M. Blanco and M.M. Phillips (San Francisco: ASP), 381
Niemela, V. S., Barbá, R. H., Morrell, N. I., & Corti, M. 1997, ASP Conf. Ser. 120, Luminous Blue Variables: Massive Stars in Transition, ed. A. Nota & H. Lamers (San Francisco: ASP), 222
Toledano, O., Moreno, E., Koenigsberger, G., Detmers, R., & Langer, N. 2006, A&A, 461, 1057
van der Hucht, K. A. 2001, NewA Rev., 45, 135
Villar-Sbaffi, A., Moffat, A. F. J., & St.-Louis, N. 2003, ApJ, 590, 483

DISCUSSION

A. Moffat: There are other sources of perturbations that should be considered, such as the heating effects from the X-rays produced at the bow-shock head between stars A and B, as we started to do in Moffat et al. (1998).

G. Koenigsberger: Wind-wind collisions and the effects associated with them are inevitable if the winds of both stars are able to accelerate to large speeds in the intervening region. However, strong tidal perturbations are also inevitable if the stellar rotation is not synchronized with the orbital angular velocity.

N. Smith: The high luminosity and high mass loss make LBV outburst and the fact that it's in a binary naturally make me think of comparing HD 5980 to Eta Car. In that case, its curious that their outbursts were so different. Namely, Eta Car ejected over 10 $M_{\odot}$ in its 19th century outburst, whereas HD 5980 only ejected about 0.001 $M_{\odot}$ that's four orders of magnitude different and it begs for an explanation, given that the primary star's luminosities and mass loss rates are within a factor of 2. One obvious difference that comes to mind is that Eta Car has a 5 year period whereas HD 5980 has amuch smaller separation with only a 19.3 day period. So I am wondering if the closer companion in HD 5980 somehow regulates the LBV instability so that it erupts more often with less mass, and therefore doesn't build up the catastrophic instability that leads to a major outburst like Eta Car. Any thoughts on that?

G. Koenigsberger: We do not know what the underlying mechanism for the instability in HD 5980 really is. If we assume that its radius is growing due to evolutionary processes, it is possible that the presence of the binary companion produces a "premature" eruption through the tidal oscillations mechanism, removing mass, and thus slowing (momentarily) the expansion. The closer the binary companion is, the more frequent such events would be expected to occur.

A. Moffat: Eta at periastron could be more similar to HD 5980, given its large eccentricity.

G. Koenigsberger: The orbital separation in HD 5980 is only $\sim$100 $R_{\odot}$.

A. Maeder: What about the chemical abundances which may tell us something on the evolutionary stage of HD 5980?

G. Koenigsberger: The Non-LTE analysis that we made on the eruptor's spectrum (Koenigsberger et al. 1998) indicates that there is a significant fraction of hydrogen. A determination of other chemical element abundances would be highly desirable.

N. Walborn: Could the star be hitting the Eddington limit as well as or instead of the Bistability limit as it tries to evolve? If there are internal magnetic fields combined with differential rotation and tidal oscillations, the effects may also be catastrophic.

G. Koenigsberger: Yes, indeed.

S. Owocki: One idea for a way to trigger a super-Eddington luminosity is that the tidal excitation of pulsations you mentioned is associated with a breaking of the spherical symmetry that is essential for blocking the radiation in the envelope. The associated clumping or "porosity" of the envelope could then allow radiation to escape from an edge, leading to super-Eddington brightening that could then drive the mass eruption.

N. Smith: Did the bolometric luminosity of HD 5980 change during its LBV outburst? Pinning that down is important for explaining the differences between this event and Eta Car. If HD 5980 stays at roughly constant L_{bol}, the likely implication is that it is crossing the bistability jump and develops a pseudophotosphere as in a normal S Dor outburst, whereas Eta Car violated the classical Eddington limit and therefore suffered a much more violent, deep seated event. In that context, does HD 5980 show any evidence for a massive circumstellar shell ejected in an ancient Eta Car-like eruption?

G. Koenigsberger: We (Koenigsberger et al. 1998, ApJ, 499, 889) derived $L_{bol} = 3\times10^6\ L_{\odot}$, but Drissen et al. (2001, ApJ, 545, 484) derived $\sim10^7$, so it is not clear whether there was a change or not.

A. Moffat: Tidal oscillations may indeed be an important trigger of the eruption of star A. But once star A reaches maximum size, it is much larger than the orbital separation. This can lead to common envelope evolution for a time, and eventually shorten the orbital period leading in the (very) short period WR+O binaries we see in the Magellanic Clouds. This means that the LBV phase may indeed be crucial for explaining WR stars, given the reduced mass-loss rates of their progenitor O-stars.

G. Koenigsberger: The common envelope phase (if we can call it that!) during the 1994 eruption lasted less than a year, probably too short to cause any changes in the orbit. But if this were to happen frequently enough...